Calculating Creepage and Clearance Early Avoids Design Problems Later

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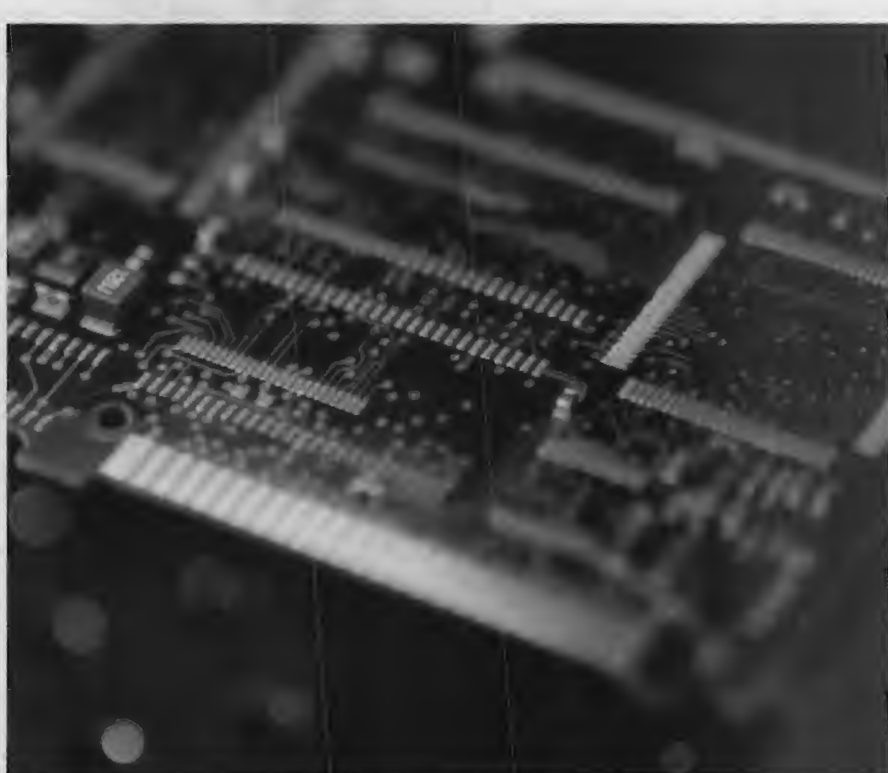
One of the most common errors uncovered by product safety engineers stems from manufacturers and designers failing to fully investigate a product's creepage and clearance distances.



It is not unusual for manufacturers to find that a product fails the creepage and clearance distance test because of miscalculations or simply because the distance between two components was overlooked. Design engineers, especially printed circuit board (PCB) designers, are often not aware of the reasons for using creepage and clearance distances. Selecting the appropriate tables in the standard and applying them properly to a design are key to avoiding problems later.

Last-minute failure can also arise because design engineers do not seek input from the product safety engineers in the early design stages. Designers sometimes assume that all safety issues relating to creepage and clearance have been addressed, only to discover spacing problems once the product is built.

Basic Definitions

Creepage Distance. Creepage is the shortest path between two conductive parts (or between a conductive part and the bounding surface of the equipment) measured along the surface of the insulation. A proper and adequate creepage distance protects against tracking, a process that produces a partially conducting path of localized deterioration on the surface of an insulating material as a result of the electric discharges on or close to an insulation surface. The degree of tracking required depends on two major factors: the comparative tracking index (CTI) of the material and the degree of pollution in the environment. Used for electrical insulating materials, the CTI provides a numerical value of the voltage that will cause failure by tracking during standard testing. IEC 112 provides a fuller explanation of tracking and CTI.[1] Tracking that damages the insulating material normally occurs because of one or more of the following reasons:

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8. A Amerasekera et al., "An Analysis of Low Voltage ESD Damage in Advanced CMOS Processes," in *Proceedings of the EOS/ESD Symposium* 12 (Lake Buena Vista, FL: ESD Association, 1990): 143–150.
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12. A Amerasekera and C Duvvury, "The Impact of Technology Scaling on ESD Robustness and Protection Circuit Design," in *Proceedings of the EOS/ESD Symposium* 16 (Las Vegas, NV: ESD Association, 1994): 237–245.
13. G Notermans, "On the Use of N Well Resistors for Uniform Triggering of ESD Protection Elements," in *Proceedings of the EOS/ESD Symposium* 19 (Santa Clara, CA: ESD Association, 1997): 222.
14. K Verhaege et al., "Analysis of HBM Testers and Specifications Using a 4th Order Lumped Element Model," in *Proceedings of the EOS/ESD Symposium* 15 (Lake Buena Vista, FL: ESD Association, 1993): 129–137.
15. SG Beebe, "Characterization, Modeling, and Design of ESD Protection Circuits," Technical Report No. ICL94-038, (Stanford, CA: Stanford University, 1994).
16. LG Henry, "Comparisons between the ESDA and the JEDEC HBM standards," Disclosures to the ESDA HBM Working Group (WG–5.2) in 1998 and 1999.
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18. A Bridgewood and Y Fu, "A Comparison of Threshold Damage Processes in Thick Field Oxide Protection Devices following Square Pulse and Human Body Model Injection," in *Proceedings of the EOS/ESD Symposium* 10 (Anaheim, CA: ESD Association, 1988): 129.
19. "Calibrating TLP Systems," Barth Electronics TLP Application Notes (Boulder City, NV: B.E. Inc. [cited 2 March 2001]). These notes can be downloaded from the Web site http://www.barthelectronics.com.

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Working Voltage (up to and including)		Nominal Ac Mains Supply Voltage ≤150 V (Mains Transient Voltage 1500 V)						Nominal Ac Mains Supply Voltage >150 V ≤300 V (Mains Transient Voltage 2500 V)						Nominal Ac Mains Supply Voltage >300 V ≤600 V (Mains Transient Voltage 4000 V)		
Peak or Dc	Rms (Sinusoidal)	Pollution Degrees 1 and 2			Pollution Degree 3			Pollution Degrees 1 and 2			Pollution Degree 3			Pollution Degrees 1, 2, and 3		
V	V	F	B/S	R	F	B/S	R	F	B/S	R	F	B/S	R	F	B/S	R
71	50	0.4	1.0 (0.5)	2.0 (1.0)	0.8	1.3 (0.8)	2.8 (1.6)	1.0	2.0 (1.5)	4.0 (3.0)	1.3	2.0 (1.5)	4.0 (3.0)	2.0	3.2 (3.0)	6.4 (8.0)
210	150	0.5	1.0 (0.5)	2.0 (1.0)	0.8	1.3 (0.8)	2.6 (1.8)	1.4	2.0 (1.5)	4.0 (3.0)	1.5	2.0 (1.5)	4.0 (3.0)	2.0	3.2 (3.0)	5.4 (6.0)
420	300	F 1.5 B/S 2.0 (1.5) R 4.0 (3.0)												2.5	3.2 (3.0)	6.4 (6.0)
840	600	F 3.0 B/S 3.2 (3.0) R 6.4 (8.0)														
1400	1000	F/BS 4.2 R 6.4														
2800	2000	F/B/S/R 8.4														
7000	5000	F/B/S/R 17.5														
9800	7000	F/B/S/R 25														
14,000	10,000	F/B/S/R 37														
28,000	20,000	F/B/S/R 80														
42,000	30,000	F/B/S/R 130														

1. The values in the table are applicable to functional (F), basic (B), supplementary (S), and reinforced (R) insulation.
2. The values in parentheses are applicable to basic, supplementary, or reinforced insulation only if manufacturing is subjected to a quality control program that provides at least the same level of assurance as the example given in annex R.2. In particular, double and reinforced insulation shall be subjected to routine tests for electric strength.
3. For working voltages between 2800 V peak or dc and 42,000 V peak or dc, linear interpolation is permitted between the nearest two points, the calculated spacing being rounded up to the next higher 0.1-mm increment.

Table I. Table 2H of the standard provides minimum clearances for insulation in primary circuits and between primary and secondary circuits (clearances in millimeters).

- Humidity in the atmosphere.
- Presence of contamination.
- Corrosive chemicals.
- Altitude at which equipment is to be operated.

Clearance Distance. Clearance is the shortest distance between two conductive parts (or between a conductive part and the bounding surface of the equipment) measured through air. Clearance distance helps prevent dielectric breakdown between electrodes caused by the ionization of air. The dielectric breakdown level is further influenced by relative humidity, temperature, and degree of pollution in the environment.

When designing a switch-mode power supply for use in information technology (IT) equipment, a typical rule of thumb is to allow an 8-mm creepage distance between primary and secondary circuits, and a 4-mm distance between primary and ground. If these dimensions are allowed for during the design stage, there is a high probability (95%) that no failure will occur with respect to creepage or clearance when the final product is submitted for test.

Working Voltages. A working voltage is the highest voltage to which the insulation under consideration is (or can be) subjected when the equipment is operating at its rated voltage under normal use conditions. The appropriate creepage and clearance values can be determined from the figures provided in the relevant tables in EN 60950.[2] These values must sometimes be calculated. To use Tables I–IV (2H, 2J, 2K, and 2L of the standard), the following factors must be considered: determination of working voltages, pollution degree of the environment, and the overvoltage category of the equipment's power source.

When measuring working voltages, it is important to measure both peak and root-mean-square (rms) voltages. The peak value is used to determine the clearance, and the rms value is used to calculate creepage. For example, if one measures a peak voltage of 670 V between two pins of a switching transformer in a switch-mode power supply, the clearance distance between primary and secondary circuits must be calculated using Table I. If the unit is powered via 240 V mains and has a pollution degree of 2, the figures in the center row (marked 300 V rms sinusoidal) and center column (since the mains voltage is >150 V and < 300 V) are used to establish the required clearance distance. In this case, the value for reinforced insulation is 4 mm. One then turns to Table II (Table 2J of EN 60950), which provides additional clearance based on the working voltages and pollution degree. (The middle column was used for calculating this example.) The appropriate row in that column covers the actual repetitive peak insulation working voltage. In this example, the value would be 0.8 mm for reinforced insulation. Adding the two figures together gives a total of 4.8 mm clearance distance. Similarly, if a voltage of 337 V rms was measured between the two pins of the switch-

Nominal Ac Mains Supply Voltage ≤150 V		Nominal Ac Mains Supply Voltage >150 V ≤300 V	Additional Clearance (mm)	
Pollution Degrees 1 and 2	Pollution Degree 3	Pollution Degrees 1, 2, and 3		
Maximum Peak Working Voltage (V)	Maximum Peak Working Voltage (V)	Maximum Peak Working Voltage (V)	Functional, Basic, or Supplementary Insulation	Reinforced Insulation
210 (210)	210 (210)	420 (420)	0	0
298 (288)	294 (293)	493 (497)	0.1	0.2
386 (366)	379 (376)	567 (575)	0.2	0.4
474 (444)	463 (459)	840 (852)	0.3	0.6
562 (522)	547 (541)	713 (729)	0.4	0.8
65 (600)	632 (624)	787 (807)	0.5	1.0
738 (678)	715 (707)	860 (884)	0.6	1.2
828 (756)	800 (790)	933 (961)	0.7	1.4
914 (839)		1006 (1039)	0.8	1.6
1002 (912)		1080 (1116)	0.9	1.8
1090 (990)		1153 (1193)	1.0	2.0
		1226 (1271)	1.1	2.2
		1300 (1348)	1.2	2.4
		— (1425)	1.3	2.6

Note: The value in parentheses shall be used when the values in parentheses in Table 2H are used in accordance with item 2 of Table 2H and for functional insulation.

Table II. Table 2J of the standard provides additional clearances for insulation in primary circuits with peak working voltages exceeding the peak value of the nominal ac mains supply voltage.

ing transformer, Table IV (2L of the standard) must be used to calculate the creepage distance between the primary and secondary circuits. Assuming pollution degree 2 and material group IIIb, the required creepage distance for basic insulation would be 3.5 mm using linear interpolation. For reinforced insulation, the values for creepage distances are double the values provided in the table for basic insulation. In this case, the required creepage for reinforced insulation would be 7 mm.

The use of these tables is explained in sections 2.10.3–2.10.4 of EN 60950. Measurements should be accurate and repeatable and should also consider the end application.

Pollution Degrees and Overvoltages

Pollution degree is divided into four categories. The following definitions are based on those in IEC 60664.[3]

- **Pollution degree 1.** No pollution or only dry, nonconductive pollution occurs. The pollution has no influence (example: sealed or potted products).
- **Pollution degree 2.** Normally only nonconductive pollution occurs. Occasionally a temporary conductivity caused by condensation must be expected (example: product used in typical office environment).
- **Pollution degree 3.** Conductive pollution occurs, or dry, nonconductive pollution occurs that becomes conductive due to expected condensation (example: products used in heavy industrial environments that are typically exposed to pollution such as dust).
- **Pollution degree 4.** Pollution generates persistent conductivity caused, for instance, by conductive dust or by rain or snow.

The overvoltage, also known as installation, category is also divided into four categories according to IEC 60664.

- **Overvoltage category I.** Signal level (special equipment or parts of equipment), with smaller transient overvoltages than overvoltage category II.
- **Overvoltage category II.** Local level (appliances and portable equipment), with smaller transient overvoltages than overvoltage category III.
- **Overvoltage category III.** Distribution level (fixed installations) with smaller transient overvoltages than overvoltage category IV.
- **Overvoltage category IV.** Primary supply level (overhead lines, cable systems, etc.). This category is not relevant to most product standards.

Typically, most standards are based on conditions being pollution degree 2 and overvoltage category II. It is important to note that as working voltage, pollution degree, overvoltage category, and altitude increase, the creepage and clearance distances also increase. The altitude is particularly important when testing to EN 61010.[4]

Creepage and Clearance in Practice

Each part of a circuit must be studied to determine the necessary insulation grade. Table 2G in EN 60950 describes common applications of insulation. For example, establishing the required creepage and clearance between a primary circuit and an ungrounded safety extra low voltage (SELV) circuit requires reinforced insulation. By measuring and establishing both the

working voltage and the pollution degree, the appropriate row and column in Table 2H (and if necessary Table 2J) determine the minimum clearance distance needed. For one test, the internal components and parts in both primary and secondary circuits are subjected to a steady force of 10 N, and certain minimum clearance distances must be maintained during the test.

Because the primary circuit is an internal circuit connected directly to the external supply mains, this circuit typically contains hazardous voltage. A secondary circuit, which has no direct connection to primary power, may or may not be hazardous. Nonhazardous circuits are classified as SELV.

Dc input products, however, can be treated in one of two ways. They can be considered as being fed by an extra-low-voltage circuit, or as hazardous secondary voltages. This would mean that the clearances could be calculated using Table III rather than Table I, requiring slightly smaller clearance distances. Dc input products can also be considered as being fed by SELV secondary circuits, depending upon the end application. If isolation is needed, then Table III of the standard is used. However, if isolation is not required in the end application, then clearances are waived, and only operational insulation is required.

Simple Design Tips

As IT products continue to get smaller, it is more important than ever to have a good and calculated PCB design that not only reduces electromagnetic interference emissions, but that also reduces creepage and clearance problems. Where shortage of space on a PCB is an issue, especially between primary and SELV circuits, techniques such as slots or grooves can be used to attain desired creepage distance. Slots must be wider than 1 mm; otherwise, they are not considered acceptable. For a groove (>1 mm wide) the only depth requirement is that the existing creepage plus the width of the groove and twice the depth of the groove must equal or exceed the required creepage distance. The slot or groove should not weaken the substrate to a point that it fails to meet mechanical test requirements.

Another solution is to design the PCB so that components are mounted flat on the board rather than positioned vertically. This layout overcomes problems that might arise from the 10-N push test required in EN 60950. A minimum of 8 mm separation between primary and secondary circuits also prevents problems. When semiconductors operating at hazardous voltages are mounted on grounded or floating heat sinks, certain precautions must be taken to ensure compliance with EN 60950. If heat sinks happen to be live (and they can be), they should be marked accordingly to warn service personnel. Generally, a semiconductor's plastic enclosure is considered as operational (necessary for correct operation of the equipment) or, in some cases, as only basic insulation. Therefore, depending on the heat sink's grounding arrangement, the semiconductor requires either basic or reinforced insulation.

It is equally important to consider creepage and clearance even when using UL-recognized power-switching semi-

Working Voltage (up to and including)		Nominal Ac Mains Supply Voltage ≤150 V (Transient Rating for Secondary Circuit 800 V)[1]						Nominal Ac Mains Supply Voltage >150 V ≤300 V (Transient Rating for Secondary Circuit 1500 V)						Nominal Ac Mains Supply Voltage >300 V ≤600 V (Transient Rating for Secondary Circuit 2500 V)[1]			Circuit Not Subject to Transient Overvoltages		
Voltage Peak or Dc	Voltage Rms (Sinusoidal)	Pollution Degrees 1 and 2			Pollution Degree 3			Pollution Degrees 1 and 2			Pollution Degree 3			Pollution Degrees 1, 2, and 3			Pollution Degrees 1 and 2 Only		
V	V	F	B/S	R	F	B/S	R	F	B/S	R	F	B/S	R	F	B/S	R	F	B/S	R
71	50	0.4 (0.2)	0.7 (0.2)	1.4 (0.4)	1.0 (0.8)	1.3 (0.8)	2.5 (1.6)	0.7 (0.5)	1.0 (0.5)	2.0 (1.0)	1.0 (0.8)	1.3 (0.8)	2.5 (1.6)	1.7 (1.6)	2.0 (1.5)	4.0 (3.0)	0.4 (0.2)	0.4 (0.2)	0.8 (0.4)
140	100	0.8 (0.2)	0.7 (0.2)	1.4 (0.4)	1.0 (0.8)	1.3 (0.8)	2.6 (1.6)	0.7 (0.5)	1.0 (0.5)	2.0 (1.0)	1.0 (0.8)	1.3 (0.8)	2.6 (1.8)	1.7 (1.5)	2.0 (1.5)	4.0 (3.0)	0.6 (0.2)	0.7 (0.2)	1.4 (0.4)
210	150	0.6 (0.2)	0.9 (0.2)	1.8 (0.4)	1.0 (0.8)	1.3 (0.8)	2.8 (1.6)	0.7 (0.5)	1.0 (0.5)	2.0 (1.0)	1.0 (0.8)	1.3 (0.8)	2.6 (1.6)	1.7 (1.6)	2.0 (1.5)	4.0 (3.0)	0.6 (0.2)	0.7 (0.2)	1.4 (0.4)
280	200	F 1.1 (0.8) B/S 1.4 (0.8) R 2.8 (1.6)												1.7 (1.5)	2.0 (1.5)	4.0 (3.0)	1.1 (0.2)	1.1 (0.2)	2.2 (0.4)
420	300	F 1.6 (1.0) B/S 1.9 (1.0) R 3.8 (2.0)												1.7 (1.5)	2.0 (1.5)	4.0 (3.0)	1.4 (0.2)	1.4 (0.2)	2.8 (0.4)
700	500	F/B/S 2.5 R 5.0																	
840	600	F/B/S 3.2 R 5.0																	
1400	1000	F/B/S 4.2 R 5.0																	
2800	2000	F/B/S/R 8.4 See [2]																	
7000	5000	F/B/S/R 17.5 See [2]																	
9800	7000	F/B/S/R 25 See [2]																	
14,000	10,000	F/B/S/R 37 See [2]																	
28,000	20,000	F/B/S/R 80 See [2]																	
42,000	30,000	F/B/S/R 130 See [2]																	

1. Where transients in the equipment exceed this value, the appropriate higher clearance shall be used.

2. Compliance with a clearance value of 8.4 mm or greater is not required if the clearance path is:
   - entirely through air, or
   - wholly or partly along the surface of an insulating material of Material Group I; and the insulation involved passes an electric strength test according to 5.2.2 using:
     - an ac test voltage whose rms value is equal to 1.06 times the peak working voltage, or
     - a dc test voltage equal to the peak value of the ac test voltage prescribed above.

If the clearance path is partly along the surface of a material that is not Material Group I, the electric strength test is conducted across the air gap only.

Table III. Table 2K of the standard provides minimum clearances in secondary circuits (clearances in millimeters).

conductors. Although these products carry a recognition mark, the manufacturer's data sheets must be examined to ensure that the components are suitable for the intended application.

The working voltages of the circuit must be taken into account. Transistors with built-in reinforced insulation (body thicker than 0.4 mm) must also still meet the spacing requirements at their legs. Some designers mistakenly assume that UL certification eliminates the need for further examination.

Troubleshooting

In some cases—in particular for switch-mode power supplies—the design topology can lead to the need for higher creepage distance in the switching transformer. In such situations, the use of a wider margin tape (also known as saddle tape) may not be practical; therefore, the use of multilayer insulated wire (also known as triple-insulated wire) is highly recommended. When using triple-insulated wire, it is important to remember that such wire must satisfy the requirements described in Annex U of EN 60950. Lack of adequate creepage and clearance distance between a component in a primary circuit to a component in the SELV circuit is a common cause of product failure. A typical short-term solution is to place an insulating material, such as Mylar sheet, with appropriate thickness and dielectric withstand voltage, between the two parts, ensuring that the sheet is mechanically secure. Room-temperature vulcanizing sealant, a silicone paste cured at room temperature, or a similar material, is used not only as a means of bonding components together for mechanical purposes, but also to overcome clearance problems. However, materials that are used to compensate for clearance problems must be UL recognized, particularly if a product is to be sold in North America.

	Functional, Basic, and Supplementary Insulation						
Working Voltage	Pollution Degree 1	Pollution Degree 2			Pollution Degree 3		
V	Material Group	Material Group			Material Group		
Rms or Dc	I, II, IIIa, or IIIb	I	II	IIIa or IIIb	I	II	IIIa or IIIb
≤50	Use the clearance from the appropriate table.	0.6	0.9	1.2	1.5	1.7	1.9
100		0.7	1.0	1.4	1.8	2.0	2.2
125		0.8	1.1	1.5	1.9	2.1	2.4
150		0.8	1.1	1.6	2.0	2.2	2.5
200		1.0	1.4	2.0	2.5	2.8	3.2
250		1.3	1.8	2.5	3.2	3.8	4.0
300		1.6	2.2	3.2	4.0	4.5	5.0
400		2.0	2.6	4.0	5.0	5.6	6.3
600		3.2	4.5	5.3	8.0	9.5	10.0
800		4.0	5.6	8.0	10.0	11.0	12.5
1000		5.0	7.1	10.0	12.5	14.0	16.0
Linear interpolation is permitted between the nearest two points, the calculated spacing being rounded to the next higher 0.1-mm increment.							

Table IV. Table 2L of the standard provides minimum creepage distances (creepage distances in millimeters).

Conclusion

Calculation and measurement of creepage and clearance distances are among the most important parts of all safety standards, and therefore it is important for design engineers to consult the product safety engineers throughout the design stages to avoid any failure at the test house before a product is launched into the market.

Creepage and clearance distances not only apply to the PCB, but also to the components (especially magnetic components) that are mounted on the PCB. It is also important to note that as working voltage, pollution degree, overvoltage category, and altitude increase, both the creepage and clearance distances also increase.

References

1. IEC 112:1979, "Method for Determining the Comparative and the Proof Tracking Indices of Solid Insulating Material under Moist Conditions," International Electrotechnical Commission, Brussels.

Experimental Evaluation of IC Susceptibility to RFI

FRANCO FIORI

Several measurement methods enable evaluation of IC susceptibility to common- and differential-mode interference, as well as radiated electromagnetic fields.

Because analog and digital integrated circuits (ICs) are widely used in equipment for electromagnetically polluted environments, as in automotive, aeronautical, and industrial systems, susceptibility to electromagnetic interference becomes a concern. An IC's power-supply distribution and intermodule communication signal cables can couple with environmental electromagnetic fields. The cables, therefore, behave as receiving antennas and collect interference superimposed on system signals.

In the case of modules composed of printed circuit boards (PCBs) with dimensions smaller than the interference wavelength, it can be assumed that interference collected by PCB traces and interference collected by IC package frames is negligible compared with that collected by connecting cables. Specifically, the amplitude of collected common-mode interference is higher than that of differential-mode interference.[1] Cables will collect common-mode interference, but failures in IC operation occur only if radio-frequency (RF) voltages are present among IC pins. In fact, PCBs translate the common-mode interference into differential mode at the IC pins.

A previous article discussed the nature of problems induced by RF interference (RFI).[2] This article presents several measurement methods. The workbench Faraday cage (WBFC) method enables evaluation of IC susceptibility to common-mode interference, and the direct-injection method provides information about IC susceptibility to differential-mode interference. The method using a transverse electromagnetic (TEM) cell allows investigation of IC susceptibility to radiated electromagnetic fields.

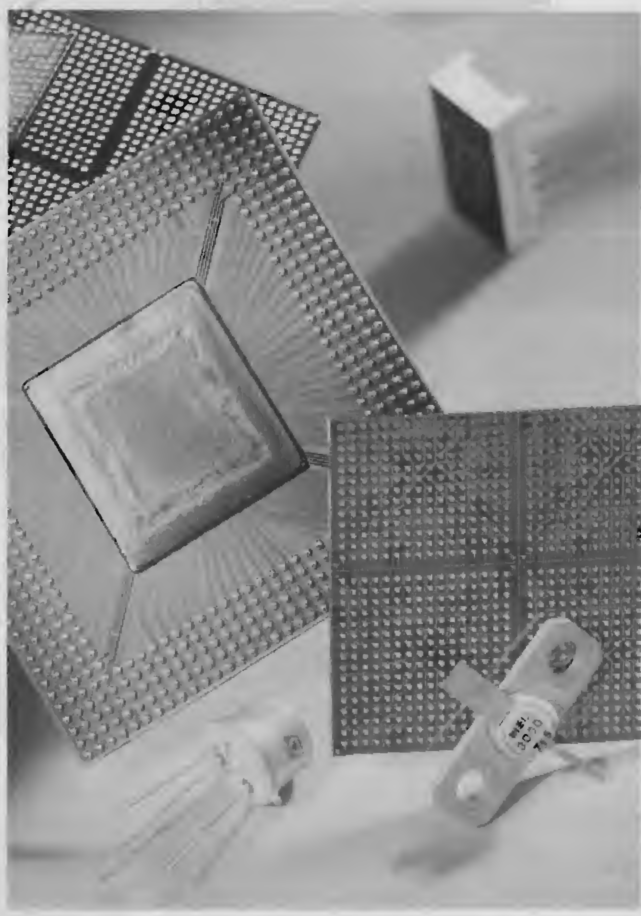

Photo by RONI RAMOS

Susceptibility Test Criteria

The evaluation of IC susceptibility to RFI can be performed by measuring the interference amplitude at the point at which device-under-test (DUT) failures occur. A second criterion consists of measuring the frequency ranges at which DUT failures occur, assuming constant amplitude of the interfering signal. The first criterion enables evaluation of the DUT functional limits due to interference. The second stems from those criteria usually adopted for verification of electrical or electronic device compliance.

Workbench Faraday Cage Method

The WBFC method was proposed to perform immunity and emission tests of ICs or small electronic modules in the